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Thompson, Mary Kathryn

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Opening Address

Challenges and Opportunities for Establishing Design as a Research Discipline in Civil and Environmental Engineering

Mary Kathryn Thompson
mkath@mek.dtu.dk
Department of Mechanical Engineering, Technical University of Denmark

Abstract: There are a number of fields including architecture, industrial design, and urban planning and design, where design is the discipline upon which all research and teaching activities are based. In other fields such as aerospace and mechanical engineering, design is a sub-discipline with its own faculty, research and education communities, conferences, and journals. However, design remains an emerging sub-discipline in civil and environmental engineering – practiced, valued, and taught but not subject to rigorous academic research. This paper presents some of the challenges associated with the establishment of design as a research discipline within civil and environmental engineering, some of the benefits and opportunities that will come from that establishment, and some evidence for the fact that this process has already begun.

Keywords: Design, Research, Education, Civil and Environmental Engineering.

Introduction

There are a number of fields including architecture, industrial design, and urban planning and design, where design is the discipline upon which all research and teaching activities are based. In other fields such as aerospace and mechanical engineering, design is a sub-discipline with its own faculty, research and education communities, conferences, and journals (Thompson 2011).

In civil and environmental engineering, design is a valued and integral part of civil engineering practice. It is an increasingly common and important part of education in CEE. And there are outlets, including the Journal of Engineering Design and Research in Engineering Design, which accept and publish research papers related to civil design. However, design is not yet a fully established research discipline with dedicated faculty, journals, conferences (or conference tracks), and qualifying exams.

This paper presents some of the challenges associated with the establishment of design as a research discipline within civil and environmental engineering, some of the benefits and opportunities that will come from that establishment, and some evidence for the fact that this process has already begun.

Multiple Types of Knowledge are Required for Engineering Design

The first challenge associated with establishing design as a research discipline is the fact that design activities require multiple types of knowledge, including but not limited to: design knowledge, domain knowledge, and knowledge about the problem to be solved.

Design Knowledge

Design knowledge includes information about various design tools and processes, their uses, and how they can be modified for specific applications. It addresses the nature of technical artifacts, the interactions between various elements within an artifact, and how an artifact's performance and characteristics change over the life cycle. It also focuses on the humans who create and interact with artifacts and how this interaction influences the design requirements, the generation of design concepts, the success of an individual artifact, and the evolution of technology in general. Some of this knowledge can be, and historically was, learned through experience. However, the goal of most design research is to develop, formalize, and validate this knowledge to improve the efficiency of the design process and the quality of the resulting artifacts.

Domain Knowledge

Domain knowledge refers to the knowledge and skills associated with the (technical) domain(s) that will be used to create the artifact. It also includes information about the environment(s) in which the artifact will function. For example, structural design requires an understanding of mechanics, materials, vibration and dynamics. Similarly, geotechnical design requires an understanding of soil mechanics, rock mechanics, hydrology and geochemistry.

Problem Knowledge

Finally, designers need a strong understanding of the specific problem that an artifact is intended to solve. Every design task involves different stakeholders, requirements, and constraints. This is particularly true in civil and environmental engineering, where every construction site has different properties and conditions. For example, the design of a bridge in a seismically active area will be substantially different from one that will be built in a region with few active faults. Similarly, the design of water resource management systems strongly depends on the local climate and the existing infrastructure.

The Relative Importance of Design, Domain and Problem Knowledge

The importance of domain knowledge relative to design knowledge is part of what separates engineering design from other design fields where design is the discipline. In the more "designerly" (Cross 2007) disciplines where form, emotion, and human interaction are emphasized, it is common for one set of individuals to develop the design concepts, for another to do the detailed design, and for a third set to produce the final artifact. This reduces the domain knowledge required by the designers and allows their training to focus almost exclusively on design knowledge. Thus, design becomes the discipline.

In engineering design, the root cause of the problem to be solved is usually technical in nature. Function often dominates other considerations. And, form and function usually cannot be separated. Thus, the designer needs strong domain knowledge to understand and define the design task and to propose concepts that can realistically address it. In addition, the design and production of the artifact often cannot be separated. This means that the designer either needs to be well versed in manufacturing (or construction) or needs to work closely with individuals who have expertise in those areas.

The importance of domain knowledge in engineering design means that these types of problems often can only be addressed by an engineer. This, combined with a lack of awareness, understanding, and appreciation of design knowledge, may be one of the reasons that design in civil and environmental engineering has typically been housed within the various silos of technical knowledge (structural engineering, geotechnical engineering, etc.) where expertise is narrow and deep (figure 1) rather than being an independent discipline where expertise is shallow but wide (figure 2).

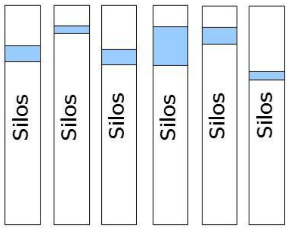

Figure 1. Design Housed within the Disciplines of Civil and Environmental Engineering

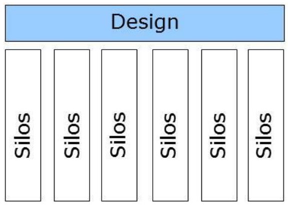

Figure 2. Design as a Sub-Discipline within Mechanical Engineering

Engineering Design is Located at the Intersection of Multiple Diverse Disciplines

The second challenge associated with the establishment of design as a research discipline is the fact that design is an interdisciplinary – and sometimes multidisciplinary – activity with domain boundaries that are often both porous and transparent.

For example, in mechanical engineering, design research generally focuses on product design, machine design, and system design. (Other types of design including material and process design are also done but generally receive less emphasis in both design research and education.) Within mechanical engineering, these areas are most closely associated with the 'harder' subjects of mechatronics, controls, and manufacturing. They also share borders with 'softer' subjects outside of engineering such as industrial design and engineering management (figure 3). This has led to a division of mechanical design into two communities: one with strong ties to manufacturing and production and the other with management and industrial design.

When viewed in the same manner, civil design can be thought of as having two main areas: structural design (bridges, buildings, dams, etc.) and system design (transportation systems, water resource management systems, etc.). Since system design is common to all systems, this forms a strong link between mechanical and civil design. On the 'softer' side, civil design is linked to architecture and urban planning, which are, in turn, linked to other 'designerly' fields such as industrial design and landscape design. Construction management and engineering has a similar relationship to civil design as manufacturing does to mechanical design.

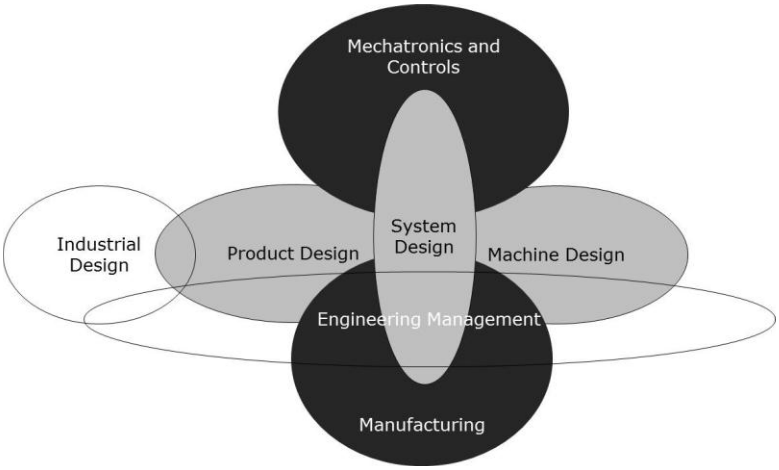

Figure 3. Design in the Field of Mechanical Engineering

These tightly coupled relationships give engineering design researchers more opportunities to publish their work because it can go to design journals, the technical domain journals, and journals associated with the final application. However, they also make it difficult to distinguish engineering design from the older and better established fields that surround it. This, in turn, makes it difficult for engineering design researchers to clearly define their expertise and thus to obtain tenure and other academic recognition.

Design Research, Practice, and Education Are Coupled

The third challenge stems from the interconnectivity of design research, practice, and education. Traditionally, engineering design was either done by individuals who had an intuitive understanding of technological artifacts and an innate ability to develop them, or by individuals who learned design through a combination of apprenticeship and experience. This model of design education was the de facto standard through the first half of the 20th century and continues to be used around the world today.

Although the apprenticeship and experience model can be an effective way to train designers, it depends almost entirely on the knowledge and skills of the master, and on his or her ability to convey that information. Mastery was, and often still is, achieved because of a natural talent for design. That talent is not necessarily accompanied by an ability to explain how and why design is done in a way that will allow others to replicate the master's success. In the absence of high quality instruction (and/or external sources of information like design textbooks), design students must rely on their own experience, intuition, and trial-and-error methods. This usually leads to a less efficient design process, increased bias, more design errors, and a lower probability of success.

The fact that design can be done without rigorous training, a formal design process, and/or an understanding of design theory and methodology is often used to argue that formal design knowledge is unnecessary and that design cannot (or should not) be taught. However, the high failure rate of new companies, technologies, and systems is a clear indication that there is still much to be learned about engineering design.

Modern design education varies by field. The more designerly disciplines such as architecture and industrial design teach design through a combination of history, case studies, design practice in a studio environment, and dialogue with professional designers. In contrast, leading engineering design programs combine design theory and methodology with design practice that usually culminates in a simulation or build-and-test verification step. In both cases, the challenge is that design education requires the faculty to teach the students how to do (and identify) 'good' design – something that is not well understood and generally not agreed upon by researchers and practitioners in the field. For this reason, design education is, and must be, informed by design research (in addition to design history and design practice).

At the same time, design researchers rely heavily on classroom settings to study design students as they apply new tools and methods to a wide range of problems and to identify the shortcomings of current design knowledge. The result is that engineering design researchers often move fluidly between the engineering and engineering education domains and their associated conferences and journals. This brings an important added benefit; design education researchers are able to bring back other contributions from the educational research community (pedagogical methods to improve content delivery, increase participation and retention, strengthen team work, improve assessment, etc.) that can inform and improve engineering education in general.

There is plenty of evidence that design education is increasingly valued and included in both traditional and non-traditional civil and environmental engineering curricula and that research in civil design education is being done (Benedetti *et al* 2013; Einstein 2013; Jensen and Almegaard 2011; Ni *et al.* 2011; Solis *et al.* 2012, Wu *et al*. 2011). However, the role of design research in informing and improving design education is only starting to be seen and appreciated.

When and How to Specialize in Engineering Design?

These three challenges raise important questions about how and when to specialize in engineering design. If we accept that all engineering designers must have a solid foundation in the engineering fundamentals, then it stands to reason that undergraduate students should focus on at least one of the traditional technical silos rather than pursuing a design specialty early in their careers. To do otherwise carries the risk that the students will not be true engineers when they graduate, but rather generalists with some exposure but no disciplinary expertise in either design or engineering. The importance of the engineering foundation is clear in light of the fact that all of the great engineering design theorists of the 20th century had strong technical backgrounds (in manufacturing engineering, computer science, cognitive psychology, etc.) that influenced their contributions in the design domain. This also implies that design education that focuses on engineering practice and the design process at the undergraduate and master's level may be different from education that prepares students to perform interdisciplinary design research at the doctoral level.

Opportunity for Exchange of Design Knowledge Between Domains

The fact that design serves as a cross-roads for different domains and disciplines means that there is great opportunity for the transfer of knowledge between CEE and other design-related fields. Design, and thus design research, depends on a number of factors including:

- The type of artifact to be designed (product, machine, system, structure, etc.)
- The physical and technical domains involved
- The size and complexity of the artifact
- The number and nature of the stakeholders involved in the design process
- The number of artifacts that will be required or produced
- The desired or required level of novelty (routine, adaptive, variant, innovative, creative, radical, etc.)
- The phase of the design process (problem specification, conceptual design, system level design, detailed design, embodiment, validation, repair and maintenance, etc.)

Mechanical engineers typically design small to medium sized artifacts for mass production. In contrast, civil engineers typically design large (mega scale) custom artifacts for populations with a large number of stakeholders who have conflicting requirements. This means that there is great potential to expand our understanding of design by applying existing design theories and methodologies from mechanical engineering to the civil domain. And, there is much that has already been learned in other design domains that can be taught to teach the civil design community.

Opportunity for Maximum Impact

Most of the great challenges of the 21st century are tied more strongly to civil and environmental engineering than mechanical engineering. These challenges include:

- Energy independence
- Environmental sustainability
- Availability of clean water
- Climate change
- The evolution of the built environment
- Aging infrastructure in more developed nations
- The rapid development of less developed nations

Thus, the greatest potential for designers and design researchers to have a positive impact on society will be in the realm of civil and environmental engineering rather than in mechanical engineering.

The Process Has Already Begun

There is substantial evidence that interdisciplinary exchanges between mechanical design and manufacturing and civil design and construction management are taking place and have been for some time. From a practical perspective, the concepts associated with lean manufacturing (Jones and Roos 1990) were rapidly adopted by the construction management industry (Ballard and Howell 1994). Similarly, additive manufacturing (Kruth *et al.* 1998) was quickly adapted for the construction industry (Khoshnevis 2004). From a more theoretical perspective, Axiomatic Design Theory (Suh 1978, 1990, 2001) is increasingly being used in architectural, building, and structural design (Albano and Suh 1992; Pastor and Benavides 2011; Gilbert *et al.* 2013; Marchesi *et al.* 2013), urban planning (Monizza *et al.* 2013), transportation (Baca *et al*. 2013, Thompson *et al.* 2009a; Thompson *et al.* 200b; Thompson and Doroshenko 2010; Yi and Thompson 2011), water resource management (Ibragimova *et al.* 2009; Pena *et al.* 2010), and construction management (Dallasega *et al.* 2013). These exchanges have not only led to new insights into the civil design process, they have also highlighted the limitations of existing design theories and identified opportunities to improve and expand those theories. This will ultimately pave the way for a more universal understanding of design and establish design as the "science of the artificial" as Herbert Simon (1969) intended.

Conclusions

Although a small community surrounding design research and education in civil and environmental engineering has begun to form, it is important to provide a forum where researchers from civil and environmental engineering can discuss design research in a supportive and interdisciplinary environment. The Second International Workshop on Design in Civil and Environmental Engineering is intended to provide that support and to help its participants lay the foundation for a civil design research community that will improve our understanding of engineering design and design education in civil and environmental engineering and beyond.

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